Duality and Chiral Restoration from Low-Mass Dileptons at the CERN-SpS

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We review recent theoretical progress in low-mass dilepton production at CERN-SpS energies. Various hadronic approaches to calculate the vector correlator in hot/dense hadronic matter are discussed and confronted with each other. Possible consequences for the nature of chiral restoration are indicated.

1. Introduction

The spectra of dileptons as penetrating probes in ultra-relativistic heavy-ion collisions (URHIC's) are expected to provide important information on the properties of QCD under conditions of extreme temperature and density, associated with the possible occurrence of the chiral/deconfinement phase transition(s). Depending on the dilepton invariant mass region under consideration, various signatures related to different properties of the strong interactions may be studied.

At high invariant masses, $M_{ll} \geq 3$ GeV, the interest is attached to the heavy quark flavors charm and bottom and the experimental focus is on the behavior of the heavy quarkonium bound states such as J/Ψ and Υ . In a possible formed quark-gluon plasma the color interaction of their constituents $(c\bar{c} \text{ or } b\bar{b})$ is believed to be Debye-screened, eventually causing a dissolution of the bound state. Thus a depletion of the J/Ψ (or Υ) resonance structures in the dilepton spectrum might signal the liberation of color charges, *i.e.*, deconfinement. This important topic has been covered in several talks in the plenary [1,2] and parallel sessions [3].

The intermediate mass region (IMR), which extends from about 1 GeV up to the $c\bar{c}$ threshold at 3 GeV, has long been proposed [4] as the suitable window to observe an increased yield of thermal radiation from an equilibrated quark-gluon plasma through $q\bar{q}$ annihilation of the light flavors q=u,d,s. On the one hand, hard processes such as Drell-Yan (DY) annihilation are already sufficiently suppressed, and, on the other hand, hadronic decay contributions are concentrated at smaller masses; moreover, the sensitivity of the IMR on temperature through thermal factors $\propto \exp(-M/T)$ strongly favors the contributions from early stages at high temperatures. The most important background besides DY pairs is due to associatedly produced D and \bar{D} mesons ('open charm'). An anomalously increased open charm contribution has been suggested to be the origin of

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the observed IMR enhancement in Pb+Pb collisions [5], but thermal radiation seems to be the more natural explanation (we will briefly return to this issue at the end).

Finally, the low-mass region (which is the main subject of this talk, see also Ref. [6] for a recent review) is characterized by the non-perturbative physics of the light (constituent) quarks and their bound states building up the low-lying hadronic spectrum. The crucial feature that governs the strong interactions in this energy regime is the (approximate) chiral symmetry of the QCD Lagrangian being spontaneously broken in the ground state of the theory as revealed by the formation of the chiral quark condensate and the absence of equal-mass chiral partners among hadrons. The occurrence of a chiral phase transition restoring the symmetry, as clearly evident from state-of-the-art lattice calculations, thus necessarily implies a substantial reshaping of the light hadron spectrum. From dilepton observables in URHIC's one hopes to witness this through the direct decays of the light vector mesons, $\rho, \omega, \phi \to l^+ l^-$. Here, owing to the inherent time scales of 10-20 fm/c in heavy-ion reactions, the ρ meson plays the by far dominant role as it has the shortest lifetime and the largest electromagnetic decay width. A significant emphasis in this talk will therefore be on the study of ρ mesons in hot and dense matter. One key question then is to what extent its medium modifications can be related to chiral restoration, and, in particular, how the latter is realized in more general terms (e.g., do all masses $\rightarrow 0$, or do all widths $\to \infty$?). This inevitably necessitates a simultaneous treatment of the chiral partner of the ρ , the $a_1(1260)$, which, unfortunately, is limited to the theoretical level as medium modifications in the axialvector channel are difficult to extract from experiment. To eventually arrive at reliable answers, the following two strategies are essential: (a) to impose model constraints within one's favorite approach, both theoretical (symmetries and related low- $T/-\mu_B$ theorems, QCD sum rules) and phenomenological (through independent experimental information); (b) to compare various approaches and their distinct (and common) features with each other. Both are included in the discussion of the microscopic hadronic models for vector mesons/dilepton rates presented in Sect. 2, which is divided into a finite temperature and a finite density part.

In Sect. 3 we will then proceed to the application to dilepton spectra in URHIC's. This involves a further complication, namely the space-time description of the global reaction dynamics, which will be briefly addressed before comparing results to dilepton data from the SpS.

We end with some concluding remarks in Sect. 4.

2. Electromagnetic Current Correlator and Thermal Dilepton Rates

The general form of thermal dilepton production rates from a hot and dense medium can be decomposed as

$$\frac{dN_{ll}}{d^4xd^4q} = L_{\mu\nu}(q) \ W^{\mu\nu}(M, \vec{q}; \mu_B, T) \tag{1}$$

with the lepton tensor (for $m_l^2 \ll M^2 = q_0^2 - \vec{q}^2$)

$$L_{\mu\nu}(q) = -\frac{\alpha^2}{6\pi^3 M^2} \left(g_{\mu\nu} - \frac{q_{\mu}q_{\nu}}{M^2} \right) . \tag{2}$$

The hadron tensor $W^{\mu\nu}$ contains all the non-trivial information on the hadronic medium of temperature T and baryon chemical potential μ_B . It is defined via the thermal expectation value of the electromagnetic (e.m.) current-current correlator [7]

$$W^{\mu\nu}(q) = -i \int d^4x \ e^{-iq\cdot x} \ \langle \langle j_{\rm em}^{\mu}(x) j_{\rm em}^{\nu}(0) \rangle \rangle_T$$

=
$$\frac{-2}{\exp(q_0/T) - 1} \ \text{Im} \Pi_{\rm em}^{\mu\nu}(q) \ .$$
 (3)

Depending on the invariant masses probed, the e.m. correlator can be described by either using hadronic degrees of freedom (saturated by vector mesons within the well-established vector dominance model (VDM)) or the (perturbative) quark-antiquark vector correlator, *i.e.*,

$$\operatorname{Im}\Pi_{\mathrm{em}}^{\mu\nu} = \begin{cases} \sum_{V=\rho,\omega,\phi} ((m_V^{(0)})^2/g_V)^2 \operatorname{Im}D_V^{\mu\nu}(M,\vec{q};\mu_B,T) &, M \leq M_{dual} \\ (-g^{\mu\nu} + q^{\mu}q^{\nu}/M^2) (M^2/12\pi) N_c \sum_{q=u,d,s} (e_q)^2 &, M \geq M_{dual} \end{cases}$$
(4)

In vacuum the transition region is located at a 'duality threshold' of $M_{dual} \simeq 1.5$ GeV, as marked by the inverse process of e^+e^- annihilation into hadrons. We will argue below that medium effects in the correlator might be summarized as a lowering of the duality threshold in hot and dense matter.

In the remainder of this section we elucidate on various investigations that have been performed to study medium modifications in the (axial-) vector correlator, beginning with the finite temperature sector.

2.1. Hadronic Approaches I: Finite Temperature

Let us first concentrate on the model independent approaches that are typically coupled with low temperature expansions. Dey *et al.* [8] have shown that, in the chiral limit, the leading effect is a mere mixing of vector and axialvector correlators with no medium effects in the spectral shapes themselves, *i.e.*,

$$\Pi_V^{\mu\nu}(q) = (1 - \varepsilon) \,\Pi_V^{\circ\mu\nu}(q) + \varepsilon \,\Pi_A^{\circ\mu\nu}(q)
\Pi_A^{\mu\nu}(q) = (1 - \varepsilon) \,\Pi_A^{\circ\mu\nu}(q) + \varepsilon \,\Pi_V^{\circ\mu\nu}(q)$$
(5)

with $\varepsilon = T^2/6f_\pi^2$ and Π° denoting the vacuum correlators. When naively extrapolating to chiral restoration, where $\varepsilon = 1/2$, one obtains $T_c^{\chi} = 160$ MeV, close to what has been found in lattice calulations. Even more surprising is the fact that when calculating the three-momentum integrated dilepton production rate, dR/dM^2 , from Π_V in Eq. (5), it coincides with the result from perturbative $q\bar{q}$ annihilation starting from masses just beyond the ϕ resonance, cf. Fig. 1. Thus, chiral restoration is coupled to a reduction of the duality threshold from 1.5 to \sim 1 GeV, being a 'weak' temperature effect. At the same time, the light vector meson resonance structures are not affected.

Another inherently model independent analysis has been pursued by Steele, Yamagishi and Zahed (hereafter referred to as SYZ) [10] within the so-called master formula framework. It uses chiral Ward identities based on broken chiral symmetry to express

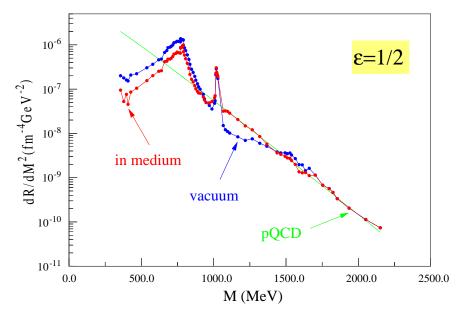


Figure 1. Three-momentum integrated dilepton production rates in hot baryon-free matter at temperature T=160 MeV using the free electromagnetic correlator (dark dots labelled 'vacuum'), the fully mixed one from Eq. (5) (light dots labelled 'in-medium') [9] and the perturbative QCD one from Eq. (4) (dashed line, 'pQCD'). Note the close agreement of the latter two between 1 and 1.5 GeV.

correlators in terms of experimentally accessible (vacuum) on-shell scattering matrix elements in connection with a virial-type pion-density expansion. The vector correlator, e.g., takes the form

$$\operatorname{Im}\Pi_{V}^{\mu\nu} = \operatorname{Im}\Pi_{V}^{\circ\mu\nu} + \frac{1}{f_{\pi}^{2}} \int \frac{d^{3}k}{(2\pi)^{3} 2\omega_{\pi}(k)} f^{\pi}(\omega_{\pi}(k); T) \langle \pi_{th} | j_{\text{em}}^{\mu} j_{\text{em}}^{\nu} | \pi_{th} \rangle$$

$$\langle \pi_{th} | j_{\text{em}}^{\mu} j_{\text{em}}^{\nu} | \pi_{th} \rangle = -4 \operatorname{Im}\Pi_{V}^{\circ\mu\nu}(q) + 2 \operatorname{Im}\Pi_{A}^{\circ\mu\nu}(k+q) - 2 \operatorname{Im}\Pi_{A}^{\circ\mu\nu}(k-q) + \cdots , \qquad (6)$$

where the integration is over on-shell pion states from the heat bath. The expansion parameter turns out to be $\kappa_{\pi} = n_{\pi}/2m_{\pi}f_{\pi}^2$, which is sufficiently small up to temperatures of about $T \simeq 140$ MeV. Clearly, Eq. (6) also exhibits the V-A mixing, which is consistent with Eq. (5) in the chiral limit.

Another class of approaches uses chiral Lagrangians to study the finite temperature behavior of (axial-) vector mesons. E.g., employing the gauged linear σ model and imposing vector dominance, Pisarski found that in the vicinity of the phase transition point, a lowest order loop expansion gives selfenergy corrections to ρ and a_1 masses such that [11]

$$m_{\rho}^{2}(T_{c}^{\chi}) = m_{a_{1}}^{2}(T_{c}^{\chi}) = \frac{1}{3}(2m_{\rho}^{2} + m_{a_{1}}^{2}) ,$$
 (7)

i.e., the masses merge in between their free values (with no dramatic changes of the in-medium widths). Another variant is the 'Hidden Local Symmetry' scheme, which in its minimal version does not include the a_1 meson. Nevertheless, the low-energy mixing theorem (5) is satisfied through temperature corrections of the VDM coupling constant,

 $g_{\rho\gamma}(T)$ [12]. The application to calculating the in-medium pion electromagnetic form factor within a low-temperature pion-loop expansion shows a strong reduction and broadening of the ρ resonance structure (with practically no mass shift), leaving a rather small enhancement in the corresponding dilepton rates towards the two-pion threshold [13].

A third avenue of finite temperature calculations proceeds with effective meson Lagrangians [14–20] where the emphasis is on incorporating all phenomenologically important scattering processes which also go beyond SU(2) chiral symmetry. This necessarily implies a less systematic implementation of the symmetry properties, although the employed interaction vertices do satisfy basic requirements of gauge invariance and soft pion theorems. Concerning the in-medium ρ spectral function, recent kinetic theory [19] as well as many-body-type calculations [20] reach quantitative consensus that in a meson gas at T=150 MeV the in-medium broadening amounts to ~ 80 MeV with insignificant mass shift.

Finally, we compare in Fig. 2 three different calculations of dilepton rates in thermal meson matter, the chiral reduction approach (SYZ), many-body spectral function calculations (RG) and an incoherent summation of individual decay rates using kinetic theory (GL). All results agree that there is a moderate (factor 3-5) enhancement over free $\pi\pi$ an-

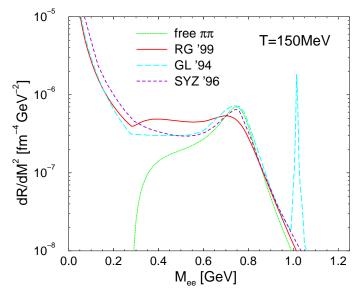


Figure 2. Three-momentum integrated dilepton production rates in hot baryon-free matter at T=150 MeV in the hadronic approaches of Gale/Lichard [15] (long-dashed line), Steele et al. [10] (short-dashed line) and Rapp/Gale [20] (full line). The dotted line represents free $\pi\pi$ annihilation.

nihilation for invariant masses below the free ρ (the somewhat larger excess from Ref. [20] being mostly due to Bose-enhancement factors in the $\rho \to \pi\pi$ width not included in the other two curves). In addition the thermal broadening in the spectral function approach entails a $\sim 30\%$ suppression in the ρ resonance region.

2.2. Hadronic Approaches II: Finite Density

The most famous approach, which integrally fueled the vigorous activity in the field, is the mean-field based analysis of Brown and Rho (BR) [21] using arguments of scale invariance of the QCD Lagrangian. It culminated in the so-called BR-scaling conjecture according to which all hadron masses (except for the Goldstone ones) follow a universal density dependence linked to order parameters of chiral restoration, f_{π} or the quark condensate, as

$$\frac{\chi^*}{\chi_0} = \frac{f_\pi^*}{f_\pi} = \frac{m_\sigma^*}{m_\sigma} = \frac{m_N^*}{m_N} = \frac{m_\rho^*}{m_\rho} = \frac{m_\omega^*}{m_\omega} \,, \tag{8}$$

where quantities with an asterisk refer to the in-medium values. χ denotes the soft component of the (scalar) glueball field which has been introduced on the effective chiral Lagrangian level to incorporate the same scaling properties as in QCD. Its vacuum expectation value χ_0 is associated with the soft part of the gluon condensate that is actually melted in the chiral transition, being realized by the vanishing of all hadron masses. This hypothesis has been successfully applied in describing the low-mass dilepton enhancement at the CERN-SpS [22,23].

The chiral reduction scheme mentioned above has also been extended to include nucleons [24]. The medium effects in the vector correlator have been inferred as

$$\Pi_V^{\mu\nu} = \Pi_V^{\circ\mu\nu} + \int \frac{d^3p}{(2\pi)^3 2E_N(p)} f^N(E_N(p); \mu_N, T) \langle N|j_{\rm em}^{\mu}|\alpha\rangle \langle \alpha|j_{\rm em}^{\nu}|N\rangle$$
(9)

through empirical information on the photon Compton tensor on the nucleon with intermediate states $|\alpha\rangle = |\pi N\rangle, |\Delta(1232)\rangle, |N(1520)\rangle$. Similar to other approaches discussed below, nucleons have been found to impact the correlator stronger than thermal pions.

Many finite density investigations have been carried out within (chiral) effective Lagrangian frameworks. The early works [25,26] have mainly focused on modifications in the pion cloud of the ρ through nucleon- and delta-hole excitations well-known from nuclear optical potentials. However, model constraints imposed from nucleon/nuclear photoabsorption data as well as $\pi N \to \rho N$ scattering data [27–30] enforced the use of rather soft πNN and $\pi N\Delta$ vertex form factors, suppressing the nuclear effects in the pion cloud of the ρ . A more important role seems to be plaid by direct ρN scattering into baryonic resonances (the so-called 'Rhosobars') as first proposed by Friman/Pirner [31] for the P-wave (parity '+') states N(1720) and $\Delta(1905)$. Also in this context, nucleon/nuclear photoabsortpion data provided valuable information marking the S-wave (parity '-') states, in particular the N(1520), as most relevant [32,29] when moving into the timelike dilepton regime. The generic result of these calculations is that the vector meson spectral functions undergo a strong broadening in cold nuclear matter. For the ρ meson at normal nuclear matter density ($\rho_0 = 0.16 \text{ fm}^{-3}$) it amounts to 200–300 MeV, which is a factor of 2–3 larger than at comparable densities in a pure meson gas.

An important theoretical consistency check on the phenomenological models can be inferred from QCD sum rule analyses. In Ref. [33] a simple Breit-Wigner parametrization for the ρ spectral function with variable width and mass has been injected into the phenomenological side to search for values that satisfy the sum rule. It turns out that there

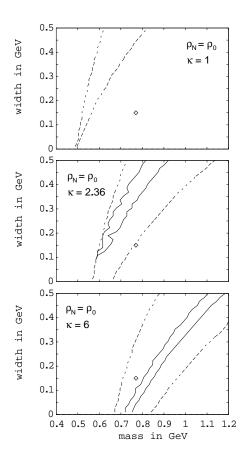


Figure 3. QCD sum rule allowed bands for in-medium ρ -mass and width [33].

is in fact no unique prediction but rather bands of allowed values in the mass-width plane, see Fig. 3 for nuclear density (dashed and solid lines border the regions where the difference between l.h.s. and r.h.s. of the sum rule is less than 1% and 0.2%, respectively). The correlation is such that one either has small mass and width (consistent with an earlier analysis [34] predicting an in-medium mass decrease), or both increasing being consistent with the hadronic model calculations discussed above as demonstrated in Ref. [27]. The detailed location of the allowed bands depends somewhat on the assumptions made about the density-dependence of the quark and gluon condensates entering the operator product expansion in the sum rule, in particular the not very well-known value of the four quark condensate encoded in the factorization parameter $\kappa = \langle \bar{q}q\bar{q}q \rangle / \langle \bar{q}q \rangle^2$. In Ref. [27] the value of 2.36 (middle panel in Fig. 3) was fixed by requiring an optimal fit to the vacuum spectrum.

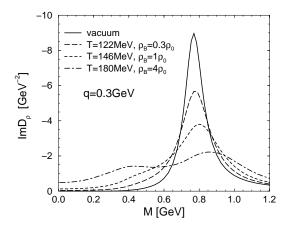
Combining the finite temperature (mesonic) and density (baryonic) effects through the various selfenergy contributions in the ρ propagator,

$$D_{\rho}(M, q; \mu_B, T) = [M^2 - (m_{\rho}^{(0)})^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B}]^{-1}, \qquad (10)$$

leads to typical results as shown in Fig. 4 [35]. The contributions to the broadening in the imaginary part are due to $\sim 30\%$ mesonic and $\sim 70\%$ baryonic effects, in particular the S-wave ρN resonances. At the highest temperature/density the second maximum structure around $M \simeq 400$ MeV is indeed due to the N(1520), which, in a selfconsistent treatment [32], builds up a large in-medium width itself. The real part of D_{ρ} (not shown) becomes very flat making the concept of a mass (defined by its zero-crossing) meaningless.

Corresponding dilepton production rates from hot and dense hadronic matter are compared with results from the chiral reduction scheme in Fig. 5. Both approaches agree on a substantial, baryon-dominated enhancement below the free ρ mass (the quantitative differences can be further traced down to different relative strengths in various subprocesses; in particular, the N(1520) contribution, being determined by photoabsorption spectra, is stronger in the RW calculations), but differ qualitatively in the ρ resonance region. This can be understood as follows: The SYZ curve, being based on a virial-type expansion, is essentially proportional to the density of the surrounding matter, $dR/dM^2 \propto (C_{\pi}n_{\pi} + C_B\varrho_B)$ with some coefficients C_{π} , C_{B} . The spectral function results behave as

$$\frac{dR}{dM^2} \propto \text{Im} D_{\rho} \propto \begin{cases} \text{Im} \Sigma_{\rho} / m_{\rho}^4 & \propto (\tilde{C}_{\pi} n_{\pi} + \tilde{C}_{B} \varrho_{B}) &, m_{\rho}^2 \gg M^2, \text{Im} \Sigma_{\rho} \\ 1 / \text{Im} \Sigma_{\rho} & \propto 1 / (\tilde{C}_{\pi} n_{\pi} + \tilde{C}_{B} \varrho_{B}) &, m_{\rho} \simeq M \end{cases}$$
(11)



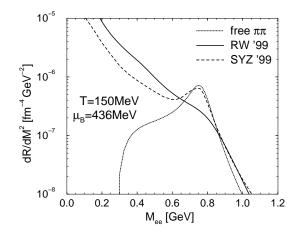


Figure 4. ρ spectral function in hot hadronic matter at fixed baryon chemical potential $\mu_B = 408$ MeV.

Figure 5. Dilepton rates in hot and dense matter ($\varrho_B=1.5\varrho_0$) within the spectral function [35] (solid line) and the chiral reduction approach [24](dashed line).

i.e., parametrically identical to the SYZ rates at low mass, but, as a consequence of the resummations in the propagator, proportional to the inverse densities in the resonance region. This strong smearing provokes yet another comparison to the perturbative $q\bar{q}$

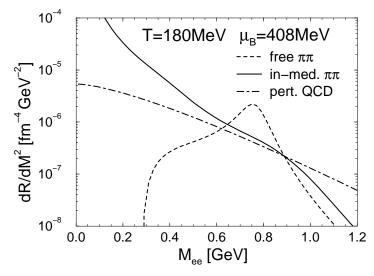


Figure 6. In-medium hadronic versus perturbative $q\bar{q}$ dilepton production rates.

annihilation rates, displayed in Fig. 6: at extreme conditions the hadronic and the partonic description indeed coincide rather well down to invariant masses of about 0.5 GeV (at masses above 1 GeV, the hadronic vector correlator, being saturated by the ρ meson, lacks the contributions from 4-pion states etc.; the agreement at very low masses might improve once soft (Bremsstrahlung-type) α_s corrections are included). Although thermal loop corrections to the partonic rates at small masses are not yet well under control, Fig. 6

seems to indicate that the duality threshold is further reduced to well below 1 GeV, this time as a consequence of 'strong' (predominantly baryon-driven) resummation effects.

3. Dilepton Spectra at CERN Energies

An evaluation of dilepton spectra in URHIC's requires the convolution of the elementary production rates (processes) over the space-time evolution of the hadronic fireball. The additional contribution from electromagnetic decays of hadrons after freezeout can be rather reliably assessed once the final state hadron abundancies are known (which is the case for π^0 's and η 's, but difficult for ω 's). Both microscopic transport and hydrodynamic simulations have been proven successful in describing the measured hadron spectra. However, as illustrated in Fig. 7, they may differ substantially in their prediction for in-medium produced dileptons, N_{ee}^{med} . Irrespective of whether the free or an

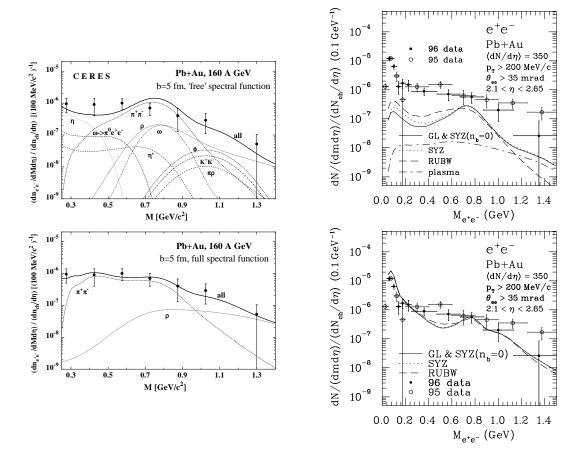
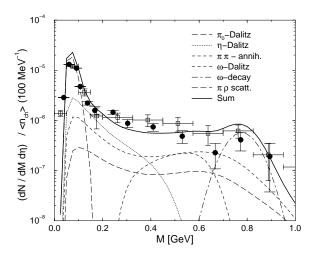


Figure 7. CERES dilepton data [36] compared to HSD transport [37] (left panel) and hydrodynamic [38] (right panel) simulations.

in-medium ρ spectral distribution is employed, the transport calculations give a factor of ~ 3 larger yields. Whereas the final pion number (fixed by experiment) is schematically given by density times fireball volume, $N_{\pi} \propto n_{\pi} V_{FB}$, in-medium dilepton radiation (arising mostly from $\pi\pi$ annihilation) behaves like $N_{ee}^{med} \propto n_{\pi}^2 V_{FB}$. The discrepancy in the latter might point at an off-equilibrium occupation of pions, *i.e.*, finite pion-chemical potential, not included in the hydro results, which as consequence do not describe the CERES data even with an in-medium spectral function. On the other hand, the transport results of Koch [39] (Fig. 8) come rather close to the low-mass enhancement around 0.4 GeV with only a rather moderate in-medium contributions. This is achieved through



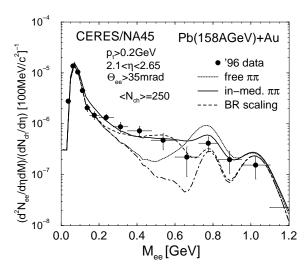


Figure 8. CERES dilepton data [36] compared to RBUU transport results [39].

Figure 9. CERES dilepton [36] data compared to thermal fireball calculations [35].

a rather large ω Dalitz decay yield, which, however, tends to imply an overestimation of the data at 0.8 GeV due to direct $\omega \to ee$ decays. The upcoming improved mass resolution/statistics measurements from CERES will be essential to clarify this issue. Fig. 9 shows thermal fireball calculations [35] where the temperature/density evolution is consistent with the recently determined *chemical* freezeout at SpS energies [40]. Using entropy and baryon number conservation, and further assuming effective pion number conservation towards *thermal* freezeout leads to the build-up of pion chemical potentials reaching almost 80 MeV. The resulting dilepton spectra (supplemented with the CERES cocktail [41](dashed-dotted line) for hadron decays after freezeout) employing either the in-medium ρ spectral function (solid line) or the dropping ρ mass conjecture (dashed line) are in reasonable agreement with experiment, which also holds for transverse momentum dependencies [35].

Finally, let us briefly comment on the implications of thermally produced dileptons for the intermediate mass region as covered, e.g., by the NA50 experiment [5]. Preliminary results of a recent calculation [42] using the same thermal fireball model as in Fig. 9 (and an approximate NA50 acceptance) indicate that the factor of \sim 3 enhancement observed in the data for $M \simeq 1.5-2.5$ GeV can indeed be accounted for without having to invoke

any 'anomalous' open charm enhancement. Note that above M=1.5 GeV there is no longer an issue of medium effects as hadronic and $q\bar{q}$ rates are 'dual' already in vacuum.

4. Conclusions

The last few years have witnessed continuous progress in understanding the in-medium properties of vector mesons and the pertinent dilepton production rates and spectra in URHIC's. It has also become clear that a profound discussion of chiral symmetry restoration needs to involve the chiral partner of the vector correlator, *i.e.*, the axialvector (a_1) channel. Low temperature theorems have shown that the leading temperature effect is a mere mixing between the two through interactions with thermal pions. When extrapolated to the phase transition region, this 'soft' temperature effect leads to an additional degeneration of hadronic and perturbative $q\bar{q}$ dilepton production rates down to masses of about 1 GeV. At lower masses a strong broadening of the ρ resonance, driven by the resummation of baryon-dominated in-medium interactions, seems to induce a further lowering of the 'duality threshold' to about 0.5 GeV. Large in-medium widths of the ρ are supported by most phenomenological calculations and are also consistent with QCD sum rules. A more rigorous link to chiral restoration requires advanced investigations of the in-medium a_1 properties.

We have furthermore shown that the broadening scenario is compatible with low-mass dilepton observables at SpS energies when employing microscopic transport calculations or thermal fireball evolutions including the build-up of moderate pion chemical potentials. However, a conclusive discrimination of the in-medium contribution in the experimental spectra can only be achieved with upcoming improved mass resolution/statistics measurements, which are essential to separate direct ω decays. Also, the commissioned 40 GeV run at the SpS will be most valuable for a more precise assessment of high baryon-density effects.

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